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Microalgae as a sustainable energy source for biodiesel production: A review

A.L. Ahmad *, N.H. Mat Yasin, C.J.C. Derek, J.K. Lim

School of Chemical Engineering, Engineering Campus, Universiti Sains Malaysia, Seri Ampangan, 14300 Nibong Tebal, Seberang Perai Selatan, Pulau Pinang, Malaysia

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ABSTRACT

Of the three generations of biodiesel feedstocks described in this paper, food crops, non-food crops and microalgae-derived biodiesel, it was found that the third generation, microalgae, is the only source that can be sustainably developed in the future. Microalgae can be converted directly into energy, such as biodiesel, and therefore appear to be a promising source of renewable energy. This paper presents a comparison between the use of microalgae and palm oil as biodiesel feedstocks. It was found that microalgae are the more sustainable source of biodiesel in terms of food security and environmental impact compared to palm oil. The inefficiency and unsustainability of the use of food crops as a biodiesel source have increased interest in the development of microalgae species to be used as a renewable energy source. In this paper, the main advantages of using microalgae for biodiesel production are described in comparison with other available feedstocks, primarily palm oil.

Contents

1. Introduction

1.1. Background

It is believed that climate change is currently the most pressing global environmental problem. Hundreds of millions of people could lose their lives and up to one million species could become extinct if the average global temperature increases by more than 2 °C [1]. It is widely accepted that using fossil fuels has caused global warming; therefore fossil fuels as a source of energy should be replaced with renewable, clean energy sources to reduce carbon dioxide and greenhouse gas emissions [2]. Other detrimental effects of global warming include a potential increase in sea level and subsequent submerging of lowlands, deltas and islands, as well as changing of weather patterns [3]. Another issue is the energy

* Corresponding author. Tel.: +60 4 5996401; fax: +60 4 5941013.
E-mail address: chlatif@eng.usm.my (A.L. Ahmad).

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crisis, in which the world suffers from lack of energy security due to depletion of the finite fossil fuel resources. The continued use of fossil fuels as a primary source of energy is now widely recognized to be unsustainable because of depleting resources and the contribution of these fuels to environmental pollution [4].

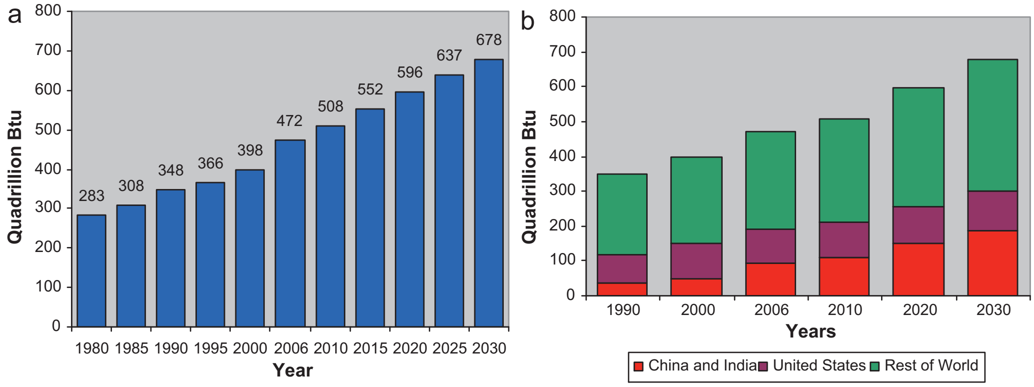

Fig. 1. (a) World marketed energy consumption. (b) Marketed energy use by region.Sources: Energy Information Administration (EIA), International Energy Annual 2006 and World Energy Projections Plus (2009).

Fig. 1 shows the world energy consumption and the energy use by region from 1980 to the present and projected through 2030. According to the Energy Information Agency (EIA) report, the world will need almost 60% more energy in 2030 than today, of which 45% will be accounted for by China and India [5]. If this trend continues, the world will be confronted with an energy crisis because the worldwide fossil oil reserves will be exhausted in fewer than 45 years. Therefore, to solve these important issues, technologies to allow substitution of fossil fuel with renewable energy should be developed.

1.2. Biodiesel

The main alternative to fossil fuel is biodiesel. The production of biodiesel has received much attention worldwide and was one of the first alternative fuels to become known to the public. Biodiesel refers to any diesel-equivalent biofuel made from renewable biological material, which usually needs a special process to transform it into a fuel. Often, biodiesel is more specifically defined as the monoalkyl esters of long-chain fatty acids derived from the chemical reaction (transesterification) of renewable feedstocks, such as vegetable oil or animal fats, and alcohol with or without a catalyst. Each biodiesel source should be evaluated on its net benefit to society based on a full life-cycle analysis that includes, among other factors, its effects on the net energy supply, the global food system, greenhouse gas emissions, soil carbon and soil fertility, water and air quality and biodiversity [6]. The total world biodiesel production was estimated to be approximately 3.8 billion liters in 2005, with approximately 85% of its production in the European Union [7].

Biodiesel is an attractive energy resource for several reasons: (1) it is a renewable fuel that could be sustainably supplied; (2) it is highly biodegradable and has minimal toxicity; (3) it appears to cause significant improvement of rural economic potential [8]; (4) it is environmentally friendly, resulting in very low sculpture release and no net increased release of carbon dioxide, aromatic compounds or other chemical substances that are harmful to the environment [4,9,10]; (5) it is better than petroleum-based diesel in terms of its lower combustion emission profile, and it does not contribute to global warming because of its closed carbon cycle; (6) it decreases dependence on foreign crude oil; (7) it can be used in existing diesel engines with little or no modification [11] and with good engine performance; (8) it can be blended in any ratio with traditional petroleum-based diesel fuel in a diesel engine [12]; (9) when added to regular diesel fuel in an amount of 1–2%, it can convert fuel with poor lubricating properties into an acceptable fuel [13]; and (10) it can provide improved combustion over petroleum-based diesel because of its high oxygen content.

The aim of this review is to investigate various sustainable energy sources for biodiesel production and determine the most suitable one. In the first part, three generations of biodiesel feedstock, food crops, non-food crops and microalgae-derived biodiesel, are briefly discussed. In the second part, we compare microalgae and palm oil, in terms of food, energy and environmental consequences, to determine the best candidate for biodiesel feedstocks. We found that microalgae are one of the most promising sustainable energy sources for biodiesel production.

2. Feedstocks of biodiesel

Biodiesel has characteristics similar to petroleum-derived diesel oil and is therefore biodiesel rated as a strong potential alternative to diesel. Because the cost of raw material accounts for about 75% of the total cost of biodiesel production (Fig. 2), choosing an appropriate feedstock is important to ensure a low biodiesel production cost. The primary biodiesel feedstocks for various regions of the world are provided in Table 1. In this section, a brief discussion of several of these biodiesel feedstocks is presented.

2.1. First generation biodiesel feedstocks

Feedstocks such as rapeseed [17], soybeans [20–22], palm oil [23–27] and sunflower [17,28,29] are considered to be first

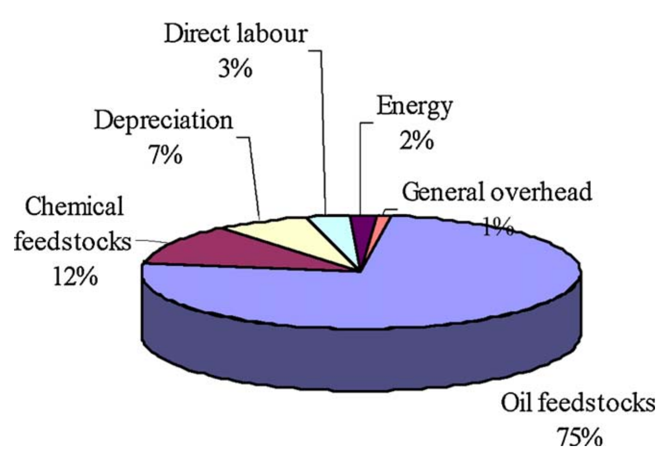

Fig. 2. General cost breakdown for production of biodiesel.Source: Ref. [14].

Table 1
Current feedstock for biodiesel worldwide.

Country/region	Feedstock	Reference
USA	Soybeans	[15,16]
Europe/EU	Rapeseed, sunflower	[16]
Western Canada	Canola oil	[19]
Africa	Jatropha	[18]
India	Jatropha	[4]
Malaysia/Indonesia	Palm	
Philippines	Coconut	[70]
China	Waste cooking oil	[70]
Spain	Linseed oil	[18]
Greece	Cottonseed	[18]

generation biodiesel feedstocks because they were the first crops to be used to produce biodiesel. Because more than 95% of this type of biodiesel is made from edible oils, the use of these first generation biodiesel sources has generated many problems, mainly due to their impact on global food markets and food security [30]. For example, palm and soy are crops whose oils are a vital part of human food. Diverting these food crops to produce oil in the large-scale production of biodiesel could bring imbalance to the global food market [31], and as a consequence, the world could suddenly face a "food versus fuel" crisis. This scenario appears to have been exaggerated in some cases; however, these oils are limited in their ability to achieve targets for biodiesel production and their use as a biofuel may cause competition with the edible oil market, which increases both the cost of edible oils and biodiesel [32].

Biodiesel production from edible oil also has a negative environmental impact because it requires that much of the available arable land be used for the production of biodiesel. Very large portions of land were needed to cultivate the first generation of biodiesel crops for them to contribute significantly to the world's fuel demand, which created serious ecological imbalances as countries around the world began cutting down forests for plantation purposes. Hence, use of these feedstocks could cause deforestation in tropical countries such as Malaysia and Indonesia that account for about 80% of the world's supply of palm oil. In fact, this trend has documented how large scale deforestation caused by the expansion of oil crops production in the past few years in order to fulfill the world's biodiesel demand. Eventually, implementation of biodiesel as a substitute fuel for petroleum-based diesel fuel could lead to extensive damage to the environment and wildlife in those regions.

2.2. Second generation biodiesel feedstocks

To reduce the dependency on edible oil, alternative biofuel sources, such as non-food feedstocks, have been developed to produce biodiesel. Energy crops such as jatropha [28,33,34], mahua [35], jojoba oil [36], tobacco seed [37], salmon oil [38] and sea mango [32] represent some of these second generation biodiesel feedstocks. Waste cooking oils, restaurant grease and animal fats [39], such as beef tallow and pork lard [40], are also considered second generation feedstocks. Production of biodiesel from non-edible oil crops has been extensively investigated over the past few years. These feedstocks have the following advantages:

- They eliminate competition for food and feed. Non-edible oils are not suitable for human food because of the presence of some toxic components in the oils [41].
- They are more efficient and more environmentally friendly than the first generation feedstocks. Conversion of non-edible oil into biodiesel is comparable to conversion of edible oils in terms of production and quality [42].
- Less farmland is required, and a mixture of crops can be used. Non-edible oil crops can be grown in wastelands that are not suitable for food crops [41].
- Useful by-products are produced, which can be used in other chemical processes or burned for heat and power.
- Animal fat methyl esters have some advantages over first generation feedstocks, such as a higher cetane number, non-corrosive qualities, clean and renewable properties [43].

Although second generation feedstocks do not typically affect the human food supply chain and can be grown in wastelands, they may not be abundant enough to replace much of our total transportation fuels. Another disadvantage of biodiesel derived from vegetable oils and animal fats is their relatively poor performance in cold temperatures. Furthermore, most animal fats contain a greater amount of saturated fatty acids, which makes transesterification difficult, resulting in problems in the production process [44]. For example, in beef tallow, the saturated fatty acid component accounts for almost 50% of the total fatty acids, which gives it the unique properties of a high melting point and high viscosity [40]. The use of animal fats as a biodiesel feedstock also presents a biosafety issue because these animal fats may come from contaminated animals [45]. For this reason, second generation feedstocks have not been produced primarily for use in biodiesel production.

2.3. Third generation biodiesel feedstocks

The cost of biodiesel production remains a major obstacle for large-scale commercial use mainly due to the high feed cost of vegetable oils [17]. Another significant concern is the inefficiency and unsustainability of these first and second generation biodiesel feedstocks [46]. Although biodiesel from oil crops has been produced in increasing amounts as a clean-burning alternative fuel, its production in large quantities is not sustainable [47]. In contrast, third generation biodiesel feedstocks, which are derived from microalgae, have emerged as one of the most promising alternative sources of lipid for use in biodiesel production because of their high photosynthetic efficiency to produce biomass and their higher growth rates and productivity compared to conventional crops [48]. In addition to their fast reproduction, they are easier to cultivate than many other types of plants and can produce a higher yield of oil for biodiesel production. As shown in Table 2 [49], microalgae grow rapidly, resulting in higher biomass productivity and oil yield compared to other oil crops. Microalgae with high oil content have the potential to produce an oil yield that is up to 25 times higher than the yield of traditional biodiesel crops, such as oil palm. Microalgae, with an oil production of at least 70% oil by weight of dry biomass, require only 0.1 m^2 year per kg biodiesel of land to produce 121,104 kg of biodiesel per year. This large production value is one reason that microalgae have been recognized as a potentially good source for biodiesel production, a process which was previously dominated by palm oil.

With the substantial processing required of fossil fuels (petroleum) and the high cost of vegetable oils, there has been much interest in algaculture (farming microalgae). The advantages of culturing microalgae as a source of transportation biodiesel include the following:

1. Enhanced efficiencies or reduction in cost. The costs associated with the harvesting and transportation of microalgae are relatively low compared to those of other biomass materials such as trees and crops. In addition, they do not directly affect the human food supply chain, eliminating the food versus fuel dispute.

Table 2
Comparison of microalgae with other biodiesel feedstocks.

Plant source	Seed oil content (% oil by wt. in biomass)	Oil yield (l oil/ha/year)	Land use (m^2 year/kg biodiesel)	Biodiesel productivity (kg biodiesel/ha/year)
Corn/Maize (*Zea mays* L.)	44	172	66	152
Hemp (*Cannabis sativa* L.)	33	363	31	321
Soybean (*Glycine max* L.)	18	636	18	562
Jatropha (*Jatropha curcas* L.)	28	741	15	656
Camelina (*Camelina sativa* L.)	42	915	12	809
Canola/rapeseed (*Brassica napus* L.)	41	974	12	862
Sunflower (*Helianthus annuus* L.)	40	1070	11	946
Castor (*Ricinus communis*)	48	1307	9	1156
Palm oil (*Elaeis guineensis*)	36	5366	2	4747
Microalgae (low oil content)	30	58,700	0.2	51,927
Microalgae (medium oil content)	50	97,800	0.1	86,515
Microalgae (high oil content)	70	136,900	0.1	121,104

Source: Ref. [49].

2. Microalgae do not compete for land with crops used for food production, fodder and other products [50]. As shown in Table 2 (column 4), the cultivation of microalgae does not require a large area of land compared to other plant sources.
3. Microalgae can be grown in a number of environments that are unsuitable for growing other crops, such as fresh, brackish or salt water or non-arable lands [46] that are unsuitable for conventional agriculture. In addition, they can be grown on farms or in bioreactors [45]. Because of this nonselective growth, microalgae produce a superior yield per hectare with improved ecological performance.
4. The most common microalgae have oil levels in the range of 20 to 50% by weight of dry biomass, but higher productivities can be reached [49]. Microalgae commonly double their biomass within 24 h, but exponential growth rates can result in a doubling of their biomass in periods as short as 3.5 h [51].
5. Microalgae produce valuable co-products or by-products such as biopolymers, proteins, carbohydrates and residual biomass, which may be used as feed or fertilizer. In addition, cultivation of microalgae does not require herbicides or pesticides [52].
6. Microalgae are considered to be an efficient biological system for harvesting solar energy to use in the production of organic compounds [53], and because of their small size, they can be easily chemically treated.
7. Microalgae are capable of fixing carbon dioxide in the atmosphere, facilitating the reduction of atmospheric carbon dioxide levels, which are now considered a global problem. In addition, microalgae biomass production can affect the biofixation of waste carbon dioxide, reducing emissions of a major greenhouse gas (1 kg of dry algal biomass requires about 1.8 kg of CO_2) [51,52].
8. Microalgae lipids are mostly neutral lipids due to their high degree of saturation, and their accumulation in the microalgal cell at different stages of growth (depending on the strain) makes microalgal lipids a potential diesel fuel substitute [54,55].

3. Comparison between microalgae and palm oil as biodiesel feedstocks

3.1. Palm oil as a source of biodiesel

Oil palm, also known as *Elaeis guineensis*, originated in West Africa but is now planted in all tropical regions of the world. Originally, it grew in the wild, but was later developed into an agricultural crop. Over the past 30 years, the worldwide area planted with oil palm has increased by more than 150%. Most of this increase has taken place in Southeast Asia, with spectacular production increases in Malaysia and Indonesia (Fig. 3). The plant was first introduced to Malaysia in the early 1870s as an ornamental plant. The first commercial oil palm estate in Malaysia was set up in 1917 at Tennamaran Estate, Selangor, laying the foundations for the vast oil palm plantations and palm oil industry in Malaysia [57]. Today, Malaysia is not only the largest producer and exporter of palm oil, but also the world's largest exporter of oils and fats. In 2008, 4.3 million hectares of land in Malaysia was used for oil palm cultivation, and 16.3 million ton of palm oil were produced that year [58]. Indonesia is a close second and is rapidly expanding, now accounting for approximately 47% of global palm oil production and 54% of the world export of this crop.

Palm oil is used as a raw material in biodiesel production. Palm oil was previously the third most widely produced edible oil, representing 10% of the global biodiesel raw material sources, after rapeseed oil (59%) and soybean oil (25%) [59]. In Malaysia, the world's largest producer and exporter of palm oil, oil palm is the "golden crop" that has helped change the biodiesel industry. This change was initiated by the Malaysian Palm Oil Board (MPOB) with a project to develop palm biodiesel at the laboratory scale in 1982 [60]. Many programs and projects regarding the utilization of oil palm biomass have been launched in Malaysia [61]:

- Small Renewable Energy Power Program (SREP)
- Biomass-based Power Generation and Co-generation in the Malaysian Palm Oil Industry (Biogen)
- EC-ASEAN COGEN Programs (co-generation programs that were economic co-operation initiated by the European Commission and the Association of South-East Asian Nations)
- Biomass Energy Plant in Lumut

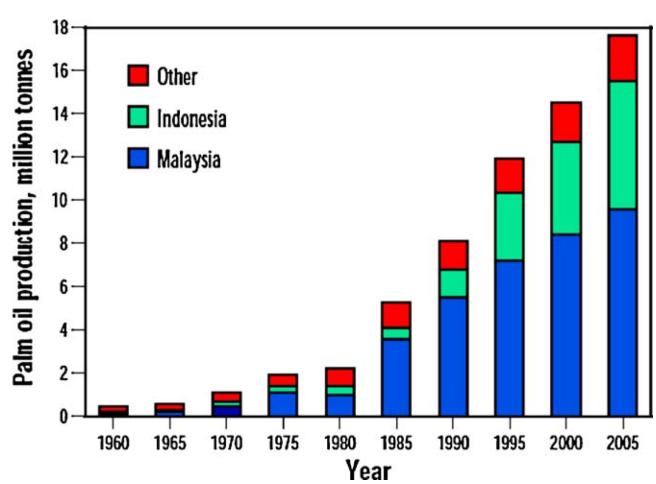

Fig. 3. Growth of oil palm production in Malaysia and Indonesia compared to the rest of the world, 1960–2005.Source: Ref. [56].

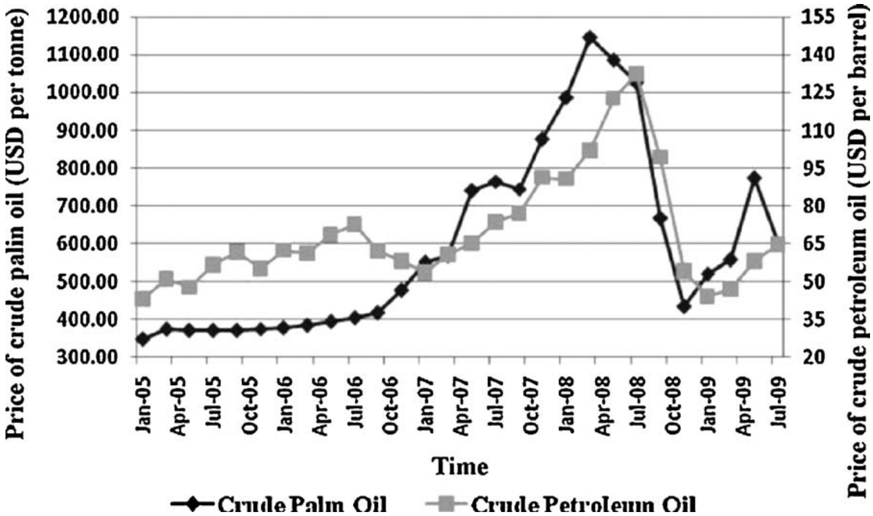

Fig. 4. Price comparison of crude palm oil and crude petroleum oil.Source: Ref. [62].

- Chubu Biomass Electric Power Plant in Malaysia
- Bio-ethanol Plant in Malaysia

3.1.1. Food versus fuel dispute for a sustainable future

Even though palm oil is an important biodiesel feedstock in tropical lowland regions, especially Malaysia, Indonesia, the Philippines, Myanmar and Thailand, its production in large quantities is not sustainable. The food versus fuel issue is one of the challenges that need to be addressed. In fact, palm oil is widely used in cooking oil and can be found in a variety of processed foods, such as margarine and biscuits and also as chemical derivatives for detergent. Conversion of large amounts of palm oil to biodiesel does compete with food production and this criticism seems to be morally wrong.

A major criticism that is often leveled against biomass is that over-dependency on palm oil for large-scale biodiesel production will consume vast swaths of farmland and native habitats and drive up the price of crude palm oil. Palm oil prices are likely to rise as biodiesel demand grows, resulting in price increases for many kinds of food. Therefore, biodiesel production from palm oil is not economically feasible.

As shown in Fig. 4 [62], it has become more difficult for biodiesel ventures to compete given the current price of crude palm oil and petroleum oil. In Malaysia, industry players comprising producers and consumers predicted that crude palm oil prices would average RM 2100 per ton in 2009, compared to RM 1500 per ton in 2008 [63]. It must also be recognized that failure to undertake a cautious, sustainable approach to the development of the biodiesel and palm oil market will do more harm than good. So that, the relative price of palm oil determines not only damaging food security, but also greatly affects biodiesel production activities.

3.1.2. Environmental debate

In addition to the food debate, there are also environmental problems created by using palm oil as a source of biodiesel, including greenhouse gas emissions, deforestation, pollution and the rate of biodegradation. In Section 2, we discussed how deforestation occurs when biodiesel is produced from food crops. In recent years, vast areas of natural forest have been cleared across tropical Asia, while deforestation has continued at a much higher pace to free more land for oil palm plantations (Fig. 5). This "land grabbing" has increased the region's vulnerability to catastrophic fires, damaging ecosystems and biodiversity and increasing the emission of climate change gases [64].

Besides the loss of forest ecosystems, the production of palm oil, as currently practiced, can be quite damaging to the environment. In 2001, Malaysia's production of 7 million tons of crude palm oil generated 9.9 million tons of solid oil wastes, palm fiber and shells, and 10 million tons of palm oil mill effluent, a polluted mixture of crushed shells, water and fat residues that has been shown to have a negative impact on aquatic ecosystems [65]. Considering that Malaysia is one of the largest producers of palm oil, the production of large quantities of palm oil may be more polluting. Increased demand for palm oil would result in additional ecological damage in Malaysia. Thus, palm oil cultivation not only impacts millions of people because of the effect on health and local culture, but also destroys orangutan habitats.

The debate is clear regarding the unsustainability of palm oil as a source of biodiesel production. In view of the opportunities presented by the biodiesel industry, all stakeholders must be aware of the effect of their industries on environmental sustainability and be prepared for the impact on our sensitive ecosystems. The Malaysian government admits to having concerns about the availability of crude palm oil (CPO) for the food and oleochemicals sectors and the extent of the potential effect on both downstream processors and consumers from the resulting increase in CPO price [66,67]. There is not enough land to be used to grow crops for food and biodiesel, while retaining the forests and other land uses that sequester carbon in huge quantities. This scenario figures the

Fig. 5. Forest clearing in forest area near the oil palm plantations in Kalimantan.Source: Ref. [65].

restriction of Malaysia to become one of the leading biodiesel producers with palm oil as the sole raw material. Thus, Malaysia would have to develop other promising feedstocks in order to ensure its security and sustainability development for the future.

3.2. Microalgae as a source of biodiesel

Tilman et al. [68] concisely summarized the food, energy and environmental implications of biofuel development. In their policy forum, they argued cogently that "biofuels done right" must be derived from feedstocks with low greenhouse gas emissions and little or no competition with food production. One such alternative is microalgae, which are likely to win on both counts. With a little water, a few nutrients and carbon dioxide, microalgae use energy from the sun to grow, easily doubling their population in a day. However, when microalgae divert energy into accumulating oil, they do not grow very fast, if at all, and when they devote their energy to growing, they do not make much oil, a trade-off that can result in little increase in the overall production of oil [69]. This trade-off has been studied by researchers who are trying to improve the cultivation of microalgae.

Certain strains of microalgae can double in size within hours. Microalgae therefore represent the highest yield biofuel crop, having the capability to produce millions of liters of biodiesel per hectare per year. This contrasts with palm oil crops, which can produce only 5950 l/ha [71]. Although not all algal oils are satisfactory for biodiesel production, but suitable oils are commonly produced [51].

3.2.1. Research activities about microalgae

Microalgae are not a new research topic in the world, but their cultivation has gained renewed attention because of the inefficiency and unsustainability of the use of conventional crops for biodiesel production. The entire production process, ranging from the cultivation of microalgae to the production of biodiesel, has been well explored in recent years. Encouraged by high oil prices and the push for alternative fuels and carbon trading, many researchers have recommended the use of microalgae in biodiesel production instead of other available feedstocks. The first crucial step in developing the microalgal process is to select an appropriate species [49]. Selection of an appropriate microalgae species can result in single-cell plants that produce 40–50% oil by weight. Table 3 presents the lipid content and productivity for various marine and freshwater microalgae species. From this table, Rodolfi et al. [52] screened 30 microalgal strains in 250 ml flask laboratory cultures to choose the best lipid producers and found that marine genus *Nannochloropsis* is one of the best candidates for algal oil production.

Many publications describing research on microalgae have been published. Several researchers have focused on the *Chlorella* sp. [72–79], which appears to be a good option for biodiesel production because they are readily available and easily cultured in the laboratory. Converti et al. [80] attempted to increase the lipid content in microalgae by varying the temperature and nitrogen concentration during the culture of *Nannochloropsis oculata* and *Chlorella vulgaris* and concluded that variation of temperature and nitrogen concentration strongly influenced the lipid content of the microalgae. Lee et al. [81] used methods including autoclaving, bead-beating, microwave, sonication and a 10% NaCl solution to identify the most effective method for lipid extraction from *Botryococcus* sp., *C. vulgaris* and *Scenedesmus* sp. They concluded that the microwave oven method was the most simple and effective means to extract the lipids from microalgae. In addition, they found that the *Botryococcus* sp. produced the highest lipid content compared to other species. However, Griffiths and Harrison [82] have found that the lipids produced by *Botryococcus braunii* are unsuitable for use in biodiesel because the hydrocarbons produced by *B. braunii* have a chain length of greater than 30 carbons.

Table 3
Biomass productivity, lipid content and lipid productivity of 30 microalgal strains cultivated in 250 mL flasks.

Algal group	Microalgae strains	Habitat	Biomass productivity (g/l/day)	Lipid content (% biomass)	Lipid productivity (mg/l/day)
Diatoms	*Chaetoceros muelleri* F&M-M43	Marine	0.07	33.6	21.8
	Chaetoceros calcitrans CS 178	Marine	0.04	39.8	17.6
	P. tricornutum F&M-M40	Marine	0.24	18.7	44.8
	Skeletonema costatum CS 181	Marine	0.08	21.0	17.4
	Skeletonema sp. CS 252	Marine	0.09	31.8	27.3
	Thalassiosira pseudonana CS 173	Marine	0.08	20.6	17.4
	Chlorella sp. F&M-M48	Freshwater	0.23	18.7	42.1
	Chlorella sorokiniana IAM-212	Freshwater	0.23	19.3	44.7
	Chlorella vulgaris CCAP 211/11b	Freshwater	0.17	19.2	32.6
	C. vulgaris F&M-M49	Freshwater	0.20	18.4	36.9
Green algae	*Chlorococcum* sp. UMACC 112	Freshwater	0.28	19.3	53.7
	Scenedesmus quadricauda	Freshwater	0.19	18.4	35.1
	Scenedesmus F&M-M19	Freshwater	0.21	19.6	40.8
	Scenedesmus sp. DM	Freshwater	0.26	21.1	53.9
	Tetraselmis suecica F&M-M33	Marine	0.32	8.5	27.0
	Tetraselmis sp. F&M-M34	Marine	0.30	14.7	43.4
	T. suecica F&M-M35	Marine	0.28	12.9	36.4
	Ellipsoidion sp. F&M-M31	Marine	0.17	27.4	47.3
	Monodus subterraneus UTEX 151	Freshwater	0.19	16.1	30.4
	Nannochloropsis sp. CS 246	Marine	0.17	29.2	49.7
Eustigmatophytes	*Nannochloropsis* sp. F&M-M26	Marine	0.21	29.6	61.0
	Nannochloropsis sp. F&M-M27	Marine	0.20	24.4	48.2
	Nannochloropsis sp. F&M-M24	Marine	0.18	30.9	54.8
	Nannochloropsis sp. F&M-M29	Marine	0.17	21.6	37.6
	Nannochloropsis sp. F&M-M28	Marine	0.17	35.7	60.9
	Isochrysis sp. (T-ISO) CS 177	Marine	0.17	22.4	37.7
	Isochrysis sp. F&M-M37	Marine	0.14	27.4	37.8
Prymnesiophytes	*Pavlova salina* CS 49	Marine	0.16	30.9	49.4
	Pavlova lutheri CS 182	Marine	0.14	35.5	50.2
Red algae	*Porphyridium cruentum*	Marine	0.37	9.5	34.8

Source: Ref. [52].

Lipid accumulation in *Scenedesmus obliquus* was studied by Mandal and Mallick [83] under various culture conditions. They concluded that the biodiesel from *S. obliquus* contains mainly saturated and mono-unsaturated fatty acids, which gives it high oxidative stability. Thus, *S. obliquus* could be considered a potential organism for biodiesel production. Gouveia and Oliveira [84] screened six types of microalgae, *C. vulgaris*, *Spirulina maxima*, *Nannochloropsis* sp., *Neochloris oleoabundans*, *S. obliquus* and *Dunaliella tertiolecta* to determine the quantity and quality of the oil to select the best oil source for biodiesel production. Of the species tested in their work, *N. oleoabundans* (freshwater microalgae) and *Nannochloropsis* sp. (marine microalgae) were determined to be suitable as raw materials for biofuel production, because of their high oil content (29.0% and 28.7%, respectively).

Demirbas [85] used a macroalga sample (*Cladophora fracta*) and a microalga sample (*Chlorella protothecoides*) to study biodiesel production from algae oils and concluded that the oil proportion from the lipid fractions of the microalga, *C. protothecoides*, is considerably higher than that of the macroalga, *C. fracta*. The heating value of the oil and the average amount of polyunsaturated fatty acids in *C. protothecoides* are also higher than those of *C. fracta*. Minowa et al. [48] studied oil production by *D. tertiolecta* using direct thermochemical liquefaction, which is one of the promising new methods for energy production from microalgae. They found that liquefaction can contribute to the creation of an energy-producing system from mass-cultivated microalgae, with the potential to mitigate global warming. Damiani et al. [86] analyzed the potential use of *Haematococcus pluvialis* as a biodiesel feedstock and determined the lipid content and fatty-acid composition of an Argentinian strain of *H. pluvialis* grown under both optimal and stressful conditions in the laboratory.

Several studies have investigated techniques to separate the biomass from the culture medium. Rossignol et al. [87] performed cross-flow microfiltration and ultrafiltration to concentrate two marine microalgae, *Haslea ostrearia* and *Skeletonema costatum*, and evaluated the effects of cross-flow velocity, transmembrane pressure, concentration and the suspension characteristics. The use of these membranes to separate microalgae biomass from its culture medium was also investigated by Petrusevski et al. [88] and Jaouen et al. [89] but in different species. Grima et al. [90] examined various methods for recovery of the microalgal biomass and the intracellular metabolites from the biomass and used a case study to illustrate the economics of recovery of eicosapentaenoic acid (EPA), an essential fatty acid from microalgae. Cell immobilization techniques, such as the use of alginate beads [91], have been explored in order to increase the overall microalgal cell concentration and productivity. Use of these techniques improves the microalgal biomass separation from the culture medium compared to suspended cell systems.

3.2.2. Briefly of biodiesel processing from microalgae

Fig. 6 shows a schematic of the production of biodiesel from microalgae. The first step is the selection of an appropriate species with the relevant properties for the specific culture conditions and products [92]. The culture conditions, including light, temperature, pH, air (carbon dioxide) and nutrient concentration, must be considered. Microalgae can be harvested using microscreens, sedimentation, centrifugation, flocculation or membrane filtration. The harvested biomass is then dried under vacuum to release water until it reaches a constant weight. The dried biomass is pulverized with a mortar and pestle before the oil is extracted. There are three well-known methods to extract the oil from microalgae: (1) expeller/press, (2) solvent extraction using chemicals and (3) supercritical fluid extraction [85]. The most popular extraction method is Soxhlet extraction using hexane as a solvent and an extraction time of 4 h. Other solvents, such as petroleum ether, ethanol or a hexane–ethanol mixture, can be used. After extraction, the oils are converted to biodiesel using one of the four primary methods: (1) direct use and blending of raw oils, (2) microemulsions (3) thermal cracking (pyrolysis) and (4) transesterification. Complete descriptions and comparisons of these methods have been provided by Ma and Hanna [40] and Leung et al. [41]. The most commonly used method is transesterification, also called alcoholysis, because transesterification of the oil to its corresponding fatty ester (biodiesel) is the most promising solution to the high viscosity problem [85]. In the transesterification process, triglycerides are first converted to diglycerides, then the diglycerides are converted to monoglycerides, and the monoglycerides are then converted to esters (biodiesel) and glycerol (by-products). Additional details about biodiesel production using microalgae can be found elsewhere [30,49].

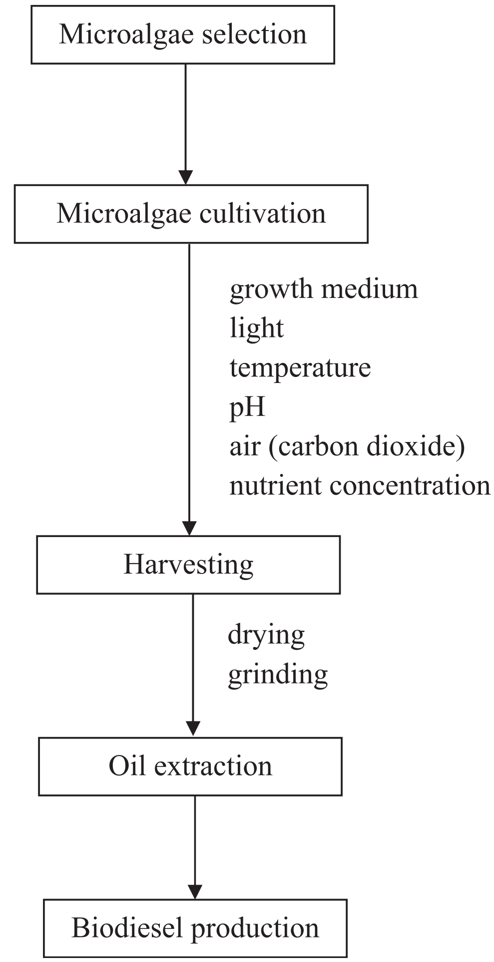

Fig. 6. Production of biodiesel from microalgae.

3.2.3. Quality of microalgae-derived biodiesel

Biodiesel produced from microalgae has been found to have properties, such as density, viscosity, flash point, cold filter plugging point, solidifying point and heating value, similar to those of petroleum-derived diesel [78]. Most of these parameters comply with the limits established by the American Society for Testing and Materials (ASTM) for biodiesel quality [10]. Algal biodiesel has also been found to meet the International Biodiesel Standard for Vehicles (EN14214). In addition, a comparison of typical properties of fossil oil and bio-oils obtained from fast pyrolysis of wood and microalgae indicated that bio-oil from microalgae (Table 4) has a higher heating value, lower viscosity and lower density compared to bio-oil from wood. The higher quality of bio-oil from microalgae compared to oils extracted from

Table 4
Comparison of typical properties of fossil oil and bio-oils from fast pyrolysis of wood and microalgae.

Properties	Typical value		
	Bio-oils		Fossil oil
	Wood	Microalgae	
C	56.4%	61.52%	83.0–87.0%
H	6.2%	8.50%	10.0–14.0%
O	37.3%	20.19%	0.05–14.0%
N	0.1%	9.79%	0.01–0.7%
S	–	–	0.05–5.0%
Density	1.2 kg/l	1.16 kg/l	0.75–1.0 kg/l
Viscosity (Pa s)	0.04-0.02 (at 40 °C)	0.10 (at 40 °C)	2–1000 (depends on factors such as temperature, density and its contents)
Heating value	21 MJ kg^{-1}	29 MJ kg^{-1}	42 MJ kg^{-1}
Stability	Not as stable as fossil fuels	Not as stable as fossil fuels, but more stable than the bio-oil from wood	

Source: Ref. [93].

lignocellulosic materials make it better suited for use as a fuel oil [93]. On the other hand, Chisti [51] reported that algal oils contain a high degree of polyunsaturated fatty acids compared to vegetable oils, which makes the algal oils susceptible to oxidation in storage, thereby limiting its utilization.

3.3. Microalgae versus palm oil in Malaysia

Taking into account growing energy consumption and domestic energy supply constraints, Malaysia has set sustainable development and diversification of energy sources as the economy's main energy policy goals. The Five-Fuel Strategy recognizes renewable energy resources as the economy's fifth most important fuel after oil, coal, natural gas and water. The ninth five-year plan (2006–2010) emphasizes the security, reliability and cost-effectiveness of the country's energy supply, while focusing on the sustainable development of the energy sector [94]. The introduction of biodiesel in the transport sector in 2005 is one of the positive steps that the government has taken to achieve sustainable energy development through diversification of fuel sources. To produce sustainable energy in the biodiesel sector, it is essential to have significant sources in case demand for biodiesel increases in the future. However, in its current state, Malaysian palm oil is not ready to be converted to diesel on a large scale, and it likely will not happen because growing palm on the large scale limits the availability of land for producing food, fodder and other crops. Because 70% of the earth's surface is covered by water, rather than land, this scenario would be different if microalgae were used as a source of biodiesel.

The idea of using microalgae as a source of fuel can be evaluated in terms of sustainability and environmental conservation in the long term. Using microalgae to produce biodiesel will not compromise production of food, fodder and other products derived from crops. Chisti [51] stated that the average annual production of microalgal biomass in a well designed production system located in a tropical zone can reach approximately 1.535 kg/m^3/day. At this level of biomass productivity, the oil yield per hectare of total land area is approximately 123 m^3. As a result, land consumption is not a major problem for microalgae cultivation, meaning that more than 90% of the land in Malaysia geographical area could be saved for other purposes. Additionally, microalgae do not have a significant environmental impact to humans and do not have much of an ecotoxic effect, such as acidification or eutrophication, which improves the sustainability of microalgae-based biodiesel.

4. Conclusion

Based on the overview presented, it is clear that the search for beneficial biodiesel sources should focus on feedstocks that do not compete with food crops, do not lead to land-clearing and provide greenhouse-gas reductions. Coherent biofuel policies must address the social context of agricultural production if biodiesel is to make a sustainable contribution toward reducing climate change and safeguarding food security. Theoretically, microalgae have been shown to be a potential source to produce third generation biodiesel because of their many advantages as a sustainable feedstock for biodiesel production; however their production needs more research to identify the most suitable microalgae species and improve their oil yield. Although any future production of biodiesel from microalgae is expected to use the same process, there is a need for more research on the biosynthesis of algal lipids, especially triglycerides and fatty acids. No other potential sources of biodiesel come close to microalgae in being realistic production for biodiesel because there were perform poorly in many environmental impacts.

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